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HARMONICALLY MODELOCKED LASER AND SYNCHRONIZED FIBER LASERS

Visionsmith, Inc.

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The harmonically modelocked laser system was synchronized with another fiber laser to establish a shared time base, and to demonstrate laser injection seeding. Synchronized pico second range pulses, such as the ones generated here, can support eventual data rates up to 100 Gigabits for phase locked laser array applications and communication links. A method of controlling the pulse rate by feedback stabilization was studied in detail. A nonlinear mechanism for shortening the pulses was experimentally tested.

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Harmonically Modelocked Laser & Synchronized Fiber Lasers

Abstract

We constructed a harmonically modelocked laser (HML) and delivered the laser to Rome Laboratory. We also made the laser operational at Rome and assisted Rome Laboratory personnel in synchronizing this laser with a second, standing wave, modelocked optical fiber laser, also at Rome. As preparation for this work we first explored various strategies and technologies relevant to constructing and stabilizing the laser. In particular, we identified and demonstrated means for active feedback controlled stabilization. The stabilization work included use of both free space and fiber passive pulse repetition rate resonators, and identified and implemented means of incorporating nonlinear shortening of pulse durations from 30 psec to 2 psec. The work described here represents initial steps toward stable long term synchronization and phase locking of multiple optical fiber modelocked lasers operating at very high repetition rates. This technology offers a potential for agile optical phased arrays capable of very high data rates in compact efficient structures.

1. Introduction

We divided this work roughly into four parts: (1) carrying out background research, (2) constructing and delivering a harmonically modelocked laser (HML) to Rome Laboratories, (3) making that laser operational at Rome Laboratories, (4) providing support for synchronization of the HML laser with a second modelocked laser at Rome Laboratory. The background research was necessary to develop the expertise and knowledge for making the lasers operational and obtaining synchronization. The background research was also helpful in training students who have and continue to support this effort.

We anticipate that harmonic modelocking [1,2]will permit versatile fiber sources. We expect these sources to allow synchronization to both external electronic clocks and to each other. We expect these sources to access very high adjustable repetition rates that extend into the multigigahertz and terahertz regimes. We have also shown that coupled modelocked laser sources, similar to these fiber lasers, can show phase locking of the carrier fields.[3] We consequently expect that both envelope synchronization and eventually carrier phase locking can be achieved.

The recent demonstration of double clad fiber amplifier technology [4] offers a remarkable opportunity for efficiently amplifying the output of these synchronized fiber

lasers. We expect agile digital optical sources of unprecedented versatility, robustness, high data rate and high average power. These double clad fibers are rapidly improving the capacity for coupling large average powers from incoherent diode bar emission into coherent single mode fiber laser emission.[4] This work helps set the stage for producing coherent arrays of these modelocked fiber lasers.

This current work addresses only synchronization; however, we believe many of the barriers to synchronization of the pulse envelopes are closely related to barriers to phase locking of the carrier fields. While phase locking at optical rates is relatively difficult we anticipate that it will eventually be possible and will further enhance the value of synchronized harmonically modelocked lasers.

This report deals with the design, construction, stabilization, and synchronization of these harmonically modelocked fiber lasers. Some particular topics addressed are implementation and evaluation of feedback technology, addition of a fiber interferometer for stabilization of the pulse train, evaluation of types of pulse repetition rate etalons, and shortening of the pulse duration by nonlinear shaping mechanisms.

2. Background

Prior to the work reported here the PI and his students had made a harmonically modelocked laser operational at the PI's laboratory at RPI.[1] In that work we introduced a free space Fabry-Perot pulse repetition rate etalon within the laser. We also determined the need for a free space delay line, but we had not yet constructed a working free space delay line nor introduced active feedback stabilization.

At the time of beginning this work, the PI and his students had performed simulations of the laser operation with a nonlinear optical loop mirror (NOLM) included. They had also shown, using calculations and experiments, that the long length of the NOLM loop tended to destabilize the laser because of the decreased mode spacing. This tended to result in multiple supermodes (particular subgroups of possible longitudinal resonator modes) oscillating within the bandpass region of a single mode of the pulse repetition rate etalon. This, in turn, allowed beating of two adjacent supermodes and resulted in laser instabilities.

We directed the work addressed in this report to realizing feedback stabilization, introducing useful free space delay lines and evaluating strategies for implementing the pulse repetition rate etalon, such as, comparison of a fiber interferometer with a free space interferometer. We also directed this work to reducing pulse duration, installing the laser at Rome Laboratory and making the laser

at Rome Laboratory operational. Additional effects during this period of performance were increasing the pump power and initiating synchronization of two lasers at Rome Laboratory.

We sought shortening of the duration of the pulses since shorter duration pulses facilitate high data rates and access to efficient nonlinear processes. We have also explored dual core fiber for shortening pulses and stabilizing the pulse trains, but found that technology is not useful at this time. We summarize immediately below the activities in chronological order by month. The performance period extended from May 94 to November 95.The Air Force granted a six months no cost extension, in part, because of delays caused by the move of our laboratory for Troy, NY to Huntsville, AL.

We began this period of performance with efforts to improve the stabilization of the harmonically modelocked laser. The laser showed modelocking, but was not stable over time. We accomplished this stabilization. We shortened the pulse duration, constructed a new version of the laser, moved the new laser to Rome Laboratory and made the laser operational there. As a final step we worked with personnel at Rome Laboratory to synchronized the laser at Rome Laboratory. Mr. Kaechele R. Erdmann were largely responsible for that final step of synchronization.

3. Construction and delivery of the HML laser

We first developed the harmonically modelocked laser at locations other than Rome Laboratory. We did extensive work exploring different aspects of the laser construction and operation. We trained personnel, including Walter Kaechele, who eventually took over the project at Rome. Once we successfully constructed a working version of the laser, including active feedback stabilization, we then constructed a version of that laser for delivery to Rome Laboratory.

We constructed the version of the HML laser delivered to Rome Laboratory at the laboratory of the PI and delivered that laser to Rome Laboratory in August of 1994. We did not make that laser operational at that time because of the lack of an adequate pump source at Rome. We did identify a number of the problems with the MOPA pump source at Rome and found solutions that worked successfully in our laboratory. We give most of the details of this work in sections 6 and 7 of this report.

4. Installation and operation of the HML laser at Rome Laboratory

We installed the version of the HML laser, constructed for Rome laboratory, in August and then made that laser operational in January of 1995. Employees of Visionsmith, including the PI, visited Rome Laboratory in August and

performed the initial installation. We then made another trip to Rome Laboratory in January to make the laser operational. Personnel at Rome Laboratory had obtained an isolator and the available pump diode power was adequate to initiate modelocked laser operation. We give most of the details of this work in sections 6 and 7 of this report.

5. Synchronization of HML laser and a second laser at Rome Laboratory

This work was carried forward and resulted in successful synchronization of the harmonically modelocked laser and the standing wave laser. This was accomplished in late summer of 1995. The PI visited Rome Laboratory during July and participated in the initial trials at synchronization.

The dynamics of the synchronized lasers were explored. This latter work was performed by Walter Kaechele, originally a student of the PI at RPI, with some collaboration with Dr. Ken Teegarden of University of Rochester, and some consulting from the PI. A pattern of Q switching of the standing wave laser was observed by Mr. Kaechele and Dr. Teegarden. The source laser is stable for short periods, but has not yet been length stabilized. We give most of the details of this work in sections 6 and 7 of this report.

Recommendations for future work are stabilizing of the laser length and shortening of the laser pulse. We suggest some potentially useful techniques possibly in sections 6 and 7. We identified and explored means for obtaining an error signal. We also identified means of introducing a correction signal by varying the length of the erbium fiber section. We accomplish this through piezoelectric stretching. We provided means for performing this fiber stretching to the personnel working on this project at Rome Laboratory.

We believe more precise electronic modulation combined with feedback stabilized length control is desirable. Others have identified excess rf frequency noise in the laser output [6] as useful error signal. We suggest that further work should consider this option.

6. Supporting technical development

We explored different aspects of the technology of these lasers and identified a particular structure that would serve the needs of Rome Laboratory. We developed expertise in constructing and operating technology for that laser, such as, fiber splicing and beam alignment. We learned these techniques and trained personnel. We solved some problems relating to efficient pump beam coupling from the MOPA into

the laser. We describe some 20 of these areas of development below.

<u>6.1 Pump source</u>

The pump for the laser was a MOPA (Master Oscillator Power Amplifier) diode operating at 985 nm. We selected the diode to operate at 985 nm so that it would pump into the strongly absorbing part of the erbium absorption band. We isolated the pump diode from the modelocked laser by introducing an Optics for Research isolator consisting of a polarizer and Faraday rotator element specifically designed for 985 nm. We made the aperture of the isolator larger than the standard commercial version so as to accommodate the full pump beam diameter. The large aperture for the isolator required special design by the supplier, Optics for Research.

<u>6.2 Means for coupling of the pump source into the fiber:</u>

We coupled the pump beam into the fiber by means of a Newport Research Corporation F1015-LD coupler. The coupler consisted of a weak input lens, a focusing objective Newport FL-10B, and means for adjusting the position of the fiber end relative to the input beam. We accomplish adjustment of the input beam by positioning a weak lens so that the motion of the lens has only a higher order effect on the beam position. This sensitivity is important in achieving optimum alignment. Optimum alignment is important in achieving the maximum performance from the laser. We typically achieved input coupling efficiencies of ~50%.

<u>6.3 Fiber for directing the pump beam from the pump diode to the input fiber coupler.</u>

We cleaved the fiber input end periodically to ensure optimum coupling. In general, the quality of the fiber end remains good; however, an occasional piece of dust or dirt can land on the fiber end and the highly focused pump power can cause burning and damage to the fiber end. Consider this as a potential problem if performance is significantly degraded. Under normally clean conditions this is relatively rare problem.It was important to use 106 Flexcore fiber to carry the pump emission to the input coupler. This 106 Flexcore fiber has a smaller core than the conventional 1.55 micron (SMF28) fiber in current communication systems. We anticipated that coupling the 980 nm pump radiation into the 106 Flexcore fiber directly (as opposed to first coupling into SMF28 fiber and then the input to the coupler) might be less efficient because of the small core size of the 106 Flexcore fiber; however, we found this was not a problem. Apparently the matching into the smaller core diameter does not cause any decreased efficiency. We found direct use of the 106 Flexcore fiber to be a significant improvement.

6.4 Fiber coupler

We used a fiber coupler made by Gould to couple the pump radiation into the harmonically modelocked. We found that coupler to function reliably and to perform as specified by the supplier. We cut the coupler leads to a relatively short length (~ 1 meter). We did this to minimize the overall length of the HML laser. Workers should take care not to cut these leads too short. This can produce leads too short to splice with the fusion splicer. This effectively makes the coupler no longer useful. In cases of this kind the remaining fiber leads should be a small integer multiple of the length required for the fusion splicer.

6.5 Ericsson fusion splicer

The splicer used to perform the splicing was an Ericsson fusion splicer. This splicer has software that makes it possible to evaluate the loss of a splice and to adjust the heating and alignment conditions so as to maximize the splice transmission. The splicer also includes a feature that optimizes splicing of erbium doped and non erbium doped fiber. This normally tends to be difficult since the erbium doped fiber has a substantially smaller core diameter than non erbium doped fiber. Alignment of the two cores and tapering of the splice is difficult without the Ericsson splicer.

The Ericsson splicer provides means to observe the fluorescence from the fiber. The splicer heats the fiber, generates luminescence, and then uses that signal to align the fiber ends. In general the cores of the fiber are not perfectly concentric with the outer cladding of the fiber. This use of the fluorescence tends to produce more transmissive fusion splices and is an essential element in preparing useful low loss harmonically modelocked lasers.

6.6 Erbium doped fiber.

We positioned the erbium doped fiber immediately after the coupler for the pump beam (Fig.1). George Harvey of AT&T Bell Laboratories provided our 20 meter length of erbium doped fiber. The erbium concentration in the fiber was relatively low and provided efficient gain at 1.55 microns. We wound the fiber on a circular cylinder and provided a cushion of plastic foam material between the core of the cylinder and the fiber. We also wound the fiber in a regular pattern. This pattern prevented the fiber strands from crossing on the cylinder. We found clearly improved laser stability on performing this careful winding of the erbium doped fiber. The reason for the improved stability is

apparently a reduction in scattering of laser mode energy by irregularities at the microbends.

6.7 Erbium luminescence as a diagnostic tool.

The visible green luminescence from the pump excited erbium doped fiber provides a useful diagnostic for aligning the HML laser and adjusting it for optimum operation. The strong luminescence provides essential information as to whether the fiber is being efficiently pumped or not. Also the brightness of the luminescence is useful in determining whether the laser is oscillating or not. The erbium excited state population decreases under laser oscillation. We identify this condition by the change (decrease) in the brightness of the visible green luminescence. This luminescence does not cause laser operation, but is valuable as a diagnostic tool.

6.8 Isolator between erbium fiber and electro-optic modulator.

After the erbium doped fiber we placed a directional isolator. We obtained the isolator from Optics for Research. We selected the isolator for operation at 1.55 microns. The isolator forced the 1.55 micron oscillator beam to pass in only one direction, i.e., counter to the pump beam direction (reverse attenuation is ~ 40 dB). and attenuated the pump emission. The attenuation of the pump is not as effective as that for the counterpropagating 1.55 micron radiation, but is helpful in reducing the magnitude of the pump radiation at the modulator. This is important because the pump is much more intense than the laser and the 985 nm pump radiation is much more likely to damage to the modulator than the 1.55 micron laser radiation. A moderate amount of light induced damage to the lithium niobate in the modulator is reversible by leaving the modulator unilluminated for a period of time (a day or so). We recommend, however, avoiding such damage as much as possible as permanent degradation of performance can occur.

6.9 Electro-optic modulator

The modulator was a AT&T litium niobate Mach-Zehnder electro-optic modulator. We drove the modulator at about 2 GHz by the signal from a Hewlett Packard 8656B signal generator. We biased the modulator by a dc signal adjustable over 0-4 volts bias. It is important not to exceed the maximum acceptable bias voltage of ~5 Volts. The bias is important in achieving optimum performance of the modulator. The bias adjusts the relative phase delays on the two paths in the interferometer so as to achieve optimum modulation. The drive signal to the modulator is about +15 dBm. One does not need the full drive for useful modulation; however,

access to the full drive signal is desirable in adjusting the laser.

There is an upper limit on the optical intensity that the modulator can tolerate. We never saw damage to the modulator; however, it is important that the modulator never see the full pump power. The threshold for damage by the shorter wavelength radiation is significantly lower than that for damage by the 1.55 micron radiation.

6.10 Control of the laser overall optical path.

We included control of the overall optical path in the fiber laser by winding an erbium doped fiber of about 20 meters length (Rome Laboratory supplied this particular fiber) on a piezoelectric ceramic ring. We made this erbium fiber and the piezoelectric ceramic ring part of the laser installed at Rome Laboratory. The piezoelectric control adjusts the length of this erbium doped fiber section over a number of optical wavelengths by varying the voltage applied to the ceramic ring. This causes the ring to expand or contract and consequently causes the erbium doped fiber to stretch or contract. One needs some bias so that the applied voltage will cause either contraction or expansion about the equilibrium condition of the ceramic-fiber system.

Undoped fiber would have worked as well for length adjustment; however, by using the erbium fiber both for the length control and for amplification we were able to make the laser shorter than otherwise possible. This is desirable as regards stability of the laser. The longitudinal modes of the fiber resonator are further apart. This makes it is easier to selectively excite one particular supermode (a specific subset of the longitudinal modes-see the discussion of the passive Fabry-Perot resonator below). Note that the electro-optic modulator included a linear polarizer. This is important for achieving optimum performance. We recommend including this polarizer at the time of purchase of the modulator if additional modulators are acquired.

6.11 Control of the polarization state of the laser.

We controlled the polarization state of the optical fields in the resonator. We accomplished this, in part, by including a polarization controller in the laser. (As noted immediately above the electro-optic modulator also included a linear polarizer that further served to fix the state of polarization at the modulator.) The adjustable polarization controller consisted of three adjustable paddles that were each wound with a few turns of fiber. The rotation of any given paddle introduces an altered birefringence in the optical path. The net result is equivalent to a series of retarder plates that are adjustable relative to each other.

This polarization controller strongly influences the performance of the laser. We placed our polarization controller immediately before the modulator. This allows us to adjust the polarization of the laser field at the input to the modulator so that it matches the linear polarization of the modulator and maximizes transmission through the modulator.

6.12. Passive resonator for controlling the repetition rate of the laser.

We also included a passive sub-resonator in the laser. This resonator assisted in stabilizing the repetition rate of the laser and also determined the particular supermode operating in the laser. The modulator determines the approximate repetition rate, but does not select a particular supermode.(Any of a large number of supermodes can produce a given repetition rate.) When properly configured this passive resonator allows only one particular supermode to oscillate. This prevents hopping of the oscillator from one supermode to another.

A necessary condition for the passive resonator to select one supermode is that only one longitudinal mode resonance fall within the pass band of the passive resonator at a given frequency. This places a requirement on the relation between the resonator quality factor and the overall length of the laser. The mode spacing of the longitudinal modes, c/nL, where nL is the integrated optical path around the fiber loop, should be large compared to the bandwidth of the passive resonator mode $c/2L_{res}F$, where L_{res} is the length of the passive resonator and F is the finesse of the passive resonator.

6.13 Mechanically adjustable path length.

We included mechanical means of adjusting the overall pathlength of the fiber laser loop. The overall length of the fiber laser loop must closely approximate an integer multiple of the passive sub resonator length. Essentially the pulses that pass through the passive resonator must maintain timing with the pulse train in the overall resonator.

This requires an adjustment of the order of L_{res} that was order of 10 cm in our system. The piezoelectric adjustment used in this system cannot correct over this large distance. We did introduce this correction by varying the length of fiber through cutting fiber; however, this tends to be tedious and difficult. The free space delay line is highly desirable for most research work.

The challenges lie in causing the mechanical movement can without misaligning the optical path. This is not trivial since the fiber alignment requires fraction of an optical wavelength precision. The mechanical travel must be of the order of the passive subresonator length, e.g., 10 cm. We accomplished this by using good mechanical stages, careful alignment, and optical mode matching.[6] We found the Newport ULTRAlign stages to be useful for holding the fiber and the Klinger mechanical stages (UMR5.16, e.g.) useful for the control of the pathlength.

6.14. Optics and matching for the free space section.

We invested considerable effort in choosing lenses for the free space section. The Newport F-L10B work well for our current configuration where the free space sections are relatively short, e.g., 10 cm. For longer free space sections one should calculate the conditions for matching into the passive resonator. The equations given in Kogelnik et al [6] are useful. We used free space sections as long as 1.5 meters in some of our exploratory systems.

6.15 Alternate means of stabilizing the resonator.

Alternate approaches to stabilizing the laser have been investigated by others and may prove preferable in the long run. The free space resonators are not easy to align and take up significant space. They have been successfully incorporated in compact stable packages by George Harvey at AT&T, but the technological effort to do this is non trivial.

One novel alternate approach is based on examining the rf beat frequency and adjusting the length of the laser so as to minimize the rf noise. This serves as a source of error signal for matching the repetition rate of the laser to the active modulating frequency. Takara [5] has used this noise as an error signal and corrected the laser length through a stepper motor so as to minimize the noise. He reports this gives highly stable operation without need for a passive resonator.

Another approach has been to introduce a frequency shift by an acousto optic modulator in the laser. The soliton action of the pulse shaping is then used to compensate for this frequency shift. Some authors find evidence of improved stability in these systems; however, the techniques does not seem to have been developed for general applied use.

6.16 Fiber interferometer.

We explored both a fiber interferometer made by Canadian Instrumentation as well as the free space interferometer. The free space interferometer has the advantage that it is

relatively flexible as regards adjustment of length. The free space interferometer is more difficult to align. Alignment also tends to require a scannable interferometer. The scannable character allows one to observe the transmission pattern during alignment of the mirrors and input coupling.

The fiber interferometer, once fusion spliced into the system, requires little further alignment. The fiber is fixed in length and does not allow significant further adjustment, other than by replacing the interferometer by a second interferometer. We adjust the coupling into the interferometer by a device provided as part of the commercially available interferometer. This adjustment is somewhat sensitive, but is not difficult. Once set this adjustment remains in a useful condition for days at a time.

The fiber interferometer is very sensitive to changes in the temperature of the loop of fiber that forms the resonator. The light path through this section is effectively multiplied by the interferometer finesse (of order 100). Hence small changes in temperature have a strong influence on the resonator length and also on the laser operation. Placing one's hand near the loop has a very strong effect on the laser operation, e.g.

6.17 Spectral control of the laser.

The spectral control of the laser was also maintained by a spectral filter, 2 nm bandpass by Omega, and a wedged etalon, (10 arcsec wedge, 1 inch diameter, 0.5 mm thickness coated at 50% reflectivity) that were included in the laser. These could be adjusted to control the operating wavelength. Translation of the wedge etalon along the direction of the wedge resulted in a fine tuning of the transmission peak. The bandwidth of the etalon was sufficient to include the full oscillating bandwidth of the laser for the longer duration pulses, (30 psec, e.g.)

6.18 Signal for feedback stabilization

The wedged etalon, in particular, was used to provide feedback control signals for stabilizing the laser. A sample of the output from the laser was divided into two beams that were passed through the wedged etalon above and below the laser beam. The difference in these two transmitted signals was used as an error signal for the feedback stabilizing circuit. A difference indicated that the frequency of the laser had shifted from a value that was centered at the transmission maximum of the wedged etalon (at the location on the etalon where the laser mode passed through the etalon).

This allowed determination of the laser frequency with sufficient precision to stabilize the laser on a single given supermode provided the laser length was not too long. We found in practice that about 30 meters was a reasonable length for the laser. This, however, made the inclusion of a NOLM loop within the laser a destabilizing influence.

6.19. Nonlinear polarization pulse shaping elements

We also explored introduction of polarization shaping elements into the laser. For a good review article see reference 7. The polarization shaping reduced the pulse duration to the order of 2 psec from 30-40 psec. We used a section of fiber for this rotation of about 20 meters in length. We used a 1/4 wave retarder plate prior to introduction of the beam into the fiber. This allows adjustment of the polarization ellipse of the incident light. We positioned a second 1/4 wave retarder and a linear polarizer in the form of a beam splitter cube after this 20 meter long section of fiber. The retarder adjusted the polarization state of the beam leaving the fiber and the polarizer ensured a particular linear polarization at the exit to this portion of the system.

We believe one could equally well achieve the polarization rotation in the erbium fiber. We suggest that in the interest of shortening the overall pathlength of the laser the erbium fiber itself serve as the element for nonlinear polarization rotation shaping.

6.20 Diagnostics

We found it important to have a scanning interferometer, an autocorrelator, a fast scope (Tektonix TDS 820), a fast detector (40 GHz), an rf spectrum analyzer (8594E HP), a lock in amplifier, and means for decoupling the scanning interferometer from the laser. The scope has 6 GHz bandwidth. This bandwidth is adequate for observing the pulse stability; however, more bandwidth would be desirable. The rf spectrum analyzer is helpful for studying noise conditions. The interferometer is essential for observing the modal distribution and the autocorrelator is essential for measuring the pulse duration.

6.21 Further technical developments

This section summarizes technical details of the work. We expect key areas for future work will be shortening pulse duration, maintaining and improving pulse train and pulse envelope stability, making more compact technology, and ruggedizing the laser structure. Promising areas are use of very compact electrically controllable delays lines, as by novel photonic band gap devices. [8]

7. Chronology of work done

We give here a chronological account of the work done. This provides a means of determining the distribution of the work in time, the work done, and the relation between the work in the PI's laboratory and that at Rome Laboratory. We performed substantial developmental work, constructed a version successfully stabilized laser, delivered the laser to Rome Laboratory, made the laser operational, and finally synchronized a second laser at Rome Laboratory to the delivered HML laser.. The final synchronization of the lasers was largely accomplished by Walter Kaechele and Reinhard Erdmann. Mr. Kaechele was initially a student of the PI at RPI and received some training in the laser technology and related skills in the PI's laboratory at RPI.

7.1 June-August 94

1. We introduced a super invar free space Fabry-Perot pulse repetition rate etalon as a means of stabilizing the pulse envelope and pulse train. The laser did not initially show increased stability. The etalon appeared to provide more stable operation, but was difficult to align. Techniques for facilitating alignment were explored. Mode matching calculations for matching the beam into the etalon were made.[6] Several techniques for performing alignment were identified.

2. We identified coupling of the harmonically modelocked laser with the diagnostic devices as a significant source of instability. We found the back reflections from the diagnostic scanning Fabry-Perot were a major source of instabilities. The variable nature of this coupling compounded this problem.

3. We introduced an Optics For Research isolator to decouple the laser from the scanning interferometer. This isolator provided 40 dB isolation at the laser wavelength and prevented reflections from the interferometer back into the source laser. Future laser designs should include some form of decoupling and isolation such as used here.

4. We found the combination of a well-aligned super invar pulse repetition rate interferometer and the isolator gave a stable laser spectrum and stable pulse envelopes for short periods of time. The isolator and a well-aligned pulse repetition rate etalon were adequate to provide stable operation for short periods of time. Thermal and mechanically induced changes in the overall laser length, however, caused the relationship of the length of the entire ring laser path and the length of the pulse repetition rate etalon to change

by more than a fraction of an optical wavelength. This caused hopping between laser supermodes.

5. We constructed a free space variable delay line. This free space variable delay line was essential to adjusting the overall laser length in relation to the length of the pulse repetition rate etalon. The laser length must be an integral number of resonator lengths for stable lasing and the overall laser length must be an integral number of optical wavelengths. The delay line facilitates achieving this condition. The design of the free space delay is demanding. We varied the optical pathlength over tens of centimeters while maintaining alignment with single mode optical fibers to precision of a fraction of a micron in the direction normal to the direction of propagation. We accomplished this; however, we required precision components and a careful alignment procedure.

6. In collaboration with Reinhard Erdmann we ordered a fiber interferometer and introduced the interferometer into the laser. The company that fabricated the interferometer was Canadian Instrumentation. The fiber interferometer is easier to install, align, and maintain in alignment, than a free space etalon. This fiber interferometer operated effectively, and required little further alignment once installed. We provided no means for controlling the polarization states of the fiber other than a polarization controller in advance of the fiber interferometer. This controller was important in obtaining optimum performance. In eventual systems polarization maintaining fiber may be necessary to make the laser optimally stable.

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7. We found the MOPA pump source, as received at Rome Laboratory to have insufficient power and stability to pump the harmonically modelocked laser. A source with this, or comparable power, is essential to providing an operating harmonically modelocked laser. We sought to determine the source of the difficulty and achieve the rated power level.

8. We found a major cause of the instability and low power from the MOPA pump source was coupling of reflected optical power from the HML system back into the output amplifier stage. Because of the high gain in the output amplifier even small back reflections from the system into the MOPA saturate the MOPA amplifier stage. This steals substantial power from the amplified signal. In turn this leads to severe reduction (e.g., 40%) in average pump power delivered to the HML laser and unstable operation. The degree of saturation depends sensitively on alignment and operating conditions.

9. We purchased and installed a custom designed Optics for Research (OFR) free space 980 nm isolator with an aperture matched to the MOPA output beam on the laser at RPI. This improved the power output and stability of the MOPA pumped laser so that it approached the specifications much more closely. We also explored alternative means of decoupling, such as angle cleaved fiber ends or spherical lenslets for beam collimation. Our exploration of these alternative means did not show an adequate solution to the instability or low power problems.

10. We introduced 106 Flexcore fiber to carry the pump radiation directly from the pump diode to the input coupler. This significantly improved the fraction of the pump power reaching the laser. We believe the reason is the mode mismatch between regular SMF 28 fiber and the 106 Flexcore used in the pump coupler. We observed a large amount of reflected power at the fiber joint where the two different fiber types meet.

11.We found the single section of 106 Flexcore fiber and the isolation of the MOPA produced stable efficient pumping. We obtained in excess of 300 mW of stable pump power in the fiber. This is significantly higher than obtained in the absence of the 106 Flexcore and the isolator. We performed this work in our laboratory. We helped introduce a similar technology at Rome Laboratory at a later stage of the work.

12. We introduced piezoelectric control of the fiber length without adding to the overall laser length. We had Canadian Instrumentation wind the erbium doped fiber on a piezoelectric cylinder. This gave us the 20 meters of fiber we needed for the gain medium. This limited the number of excited supermodes to one at any given time. This was helpful as regards stable laser operation. The electrically controlled variation in the fiber length was adequate to compensate for the typical variations in laser length.

13. We explored the use of metal coated fiber for length control. We replaced the erbium doped fiber with a metal coated erbium doped fiber of 10 meter length. The metal coated and erbium doped fiber offers means of length control at no additional price in laser length. One requires the erbium section in any laser. The metal coating provides the added feature of means for length control. The mechanism that provides the control is a change in the fiber length caused by a change in temperature of the fiber. The change in current passing through the metal coating results in a change in ohmic heating. The rate of change of length with current is rapid because of the close contact between the coating and the fiber. One obtains millisecond response times. This is an alternative to the use of the piezoelectrically controlled fiber length; however, we did not obtain sufficient gain with

the particular 10 meter long metal coated fiber. We decided not to use metal coated fiber at this time.

August

<u>14. We constructed free space delay lines for the laser in our laboratory and for the laser for Rome Laboratory.</u> We constructed a free space delay line for the laser in our laboratory and made that delay line operational. We also constructed a portable free space section including components for obtaining the error correction signal for the laser for Rome Laboratory.

<u>15. We made the feedback stabilization system operational in our laboratory using the Rome Laboratory supplied fiber interferometer and erbium fiber wound on a piezoelectrically controlled ceramic ring.</u> We obtained highly stable operation. We also performed a direct autocorrelation measurement using an autocorrelator from Rome Laboratory provided by Reinhard Erdmann. We found nearly transform limited pulses with durations of about 30 psec.

<u>16. We constructed the components for two complete lasers, besides the feedback electronics, at our laboratory.</u> We constructed components to form two complete harmonically modelocked lasers. This approach allowed us to explore related issues with the two lasers and to use the learning from the laser in our laboratory to support development of the laser at Rome Laboratory.

<u>17. We delivered the components for one HML laser to Rome Laboratory.</u> We transported the components for one HML laser to Rome Laboratory and partially assembled them at Rome. We took the components for the second laser to Huntsville, AL. We did not make the laser at Rome operational at this time, in part, because the power available from the MOPA at Rome was not then sufficient to drive the laser.

<u>18. We examined the issue of instability in the HML laser due to the interaction of the dispersive wave shed by a soliton with the soliton itself.</u> This tendency to form solitons and to shed dispersive waves is a fundamental source of instability in harmonically modelocked lasers. The solitons and the dispersive waves interact to limit the pulse duration and create instabilities. This is a limiting phenomenon that is not critical for the current laser, but could become critical as for shorter pulse duration.

<u>19. We considered soliton interactions in dual core fiber as a technology for reducing instabilities due to dispersive wave shedding.</u> The passive core of the dual core fiber provides means for removing the dispersive wave while the

soliton remains on the active core because of nonlinear mechanisms. The numerical simulations of this phenomenon reveal, however, that this condition occurs only for optical pulses of relatively short duration. One requires durations of the order of one picosecond or less. (Note: We later found that the accumulated phase difference between fields propagating on adjacent cores was sufficiently large to prevent effective use of dual core fiber given the current state of dual core fiber fabrication. One should consider use of dual core fiber in the future when workers reduce sufficiently the accumulated phase difference between cores.

20. We obtained dual core fiber from collaborators in Australia. We obtained fiber suitable for exploring dual core laser action with dispersive wave shedding from The Optical Fiber Technology Center in Sydney, Australia.

7.2 September-December 94

21. We spent the months of September, October, November and December largely in rebuilding laboratory facilities in Huntsville, AL and waiting for an isolator for use at Rome Laboratories. We reassembled the HML laser built at RPI in Troy and made the laser operational again. We also planned ways of using dual core fiber and polarization switching. We anticipated possible use of the dual core fiber for removing dispersive waves and use of polarization switching for reducing pulse duration.

22. We explored the possibility that instabilities due to microbends caused by locations in the fiber where a given fiber section crossed another fiber section on the spool holding the erbium doped fiber. Charlie Brown of AT&T at the Atlanta Bell Laboratories informed us during a visit that microbends are a non-trivial source of instabilities. The selective scattering at the micro bend perturbs the laser mode. We compared the performance of the laser when we wound the fiber on the supporting spool so as to allow crossing of fiber strands and when we wound the fiber so as to allow no crossing of fiber strands.

23. We found improved performance of the laser on winding the spool so as to avoid microbends and now use that winding technique. The pulse envelopes and pulse to pulse stability improve when we wound the erbium doped fiber so as to avoid micro bends. A key in achieving this is avoiding any crossing of the fiber over the fiber and maintaining uniform tension on the fiber. We used a highly regular winding with clear open space between turns and a soft pliable supporting material on the spool core as the support for the fiber.

24. We explored the transmission properties of the dual core fiber for picosecond optical pulses. We directed the HML output through the dual core fiber. We found coupling of measurable power to the second core. The coupling was relatively insensitive to pulse duration for pulses in this ten's of picosecond regime. The technical problem is that the core separation must be fairly large (order of 40 microns) and the pulses fairly short (order of a picosecond) so as to allow then nonlinear interaction to dominate the linear interaction.

7.3 January-March 95

25. The PI and two Visionsmith employess traveld to Rome Laboratory (January 5 and 6) and made the laser at Rome Laboratory operational. The isolator had arrived. In collaboration with Reinhard Erdmann we installed the isolator and achieved laser oscillation and modelocking. We provided training for RPI PhD candidate Walter Kaechele in operating the laser at Rome, and continued for some time to provide consultation from our Huntsville location.

26. We identified components for polarization shaping of the laser pulse. We identified and evaluated components that provide nonlinear polarization shaping in the laser. The nonlinear polarization shaping can reduce the pulse duration to a regime where dual core fiber could be effective. The shorter pulse duration may be desirable for other reasons.

February 95

27. We obtained modelocked laser operation with the dual core fiber included in the laser and set up improved diagnostics for monitoring the laser. Discussions continued with Reinhard Erdmann and Walter Kaechele at Rome Laboratory. A concern was accessing pulse durations in the picosecond regime without introducing unacceptable instabilities such as caused by dispersive wave shedding.(We determined later, see below, that the dual core allowed modelocking, but did not enhance the modelocking.)

March 95

28. We worked on construction of an autocorrelator at the Huntsville laboratory and ordered additional equipment needed for diagnostics. Discussions continued with Reinhard Erdmann and Walter Kaechele, at Rome Laboratory, concerning operation of laser at Rome. Walter Kaechele succeeded in producing pulses of 10 psec duration with the Rome Laboratory laser.

7.4 April-June 95

29. We designed combination dual core and polarization rotation pulse shaping elements for introduction into the laser. The idea here was to explore the possibility that the predicted dual core nonlinear pulse shaping mechanism may need to start with a pulse that is already relatively of the order of a picosecond duration. The polarization shaping will tend to assist in reducing the pulse duration to the point where the dual core mechanism could play a significant role.(We learned later that the accumulated phase difference in the dual core fiber caused by unavoidable differences in the two paths in the dual core fiber, as fabricated, would prevent the theoretically predicted pulse shortening and stabilization.)

May 95

30. We introduced nonlinear polarization pulse shaping and dual core fiber into the HML laser in Huntsville. We obtained evidence of reduction of the pulse duration to order of 1 psec for the system. We hoped at the time that this might make it possible to obtain both short pulses and a reduction in dispersive wave shedding.

June 95

31. We pursued this work further and determined that the dual core fiber played little or no role in the reduction of the pulse duration. We attributed all of the reduction in the pulse duration to nonlinear polarization rotation rather than to any nonlinear shaping by the dual core fiber.

32. We determined that the problem with the dual core fiber was an inability to control the accumulated phase retardation difference in the two cores over distances larger than a few centimeters. This prevents occurrence of the nonlinear shaping for dual core fiber. Our recommendation based on these findings was that the dual core fiber approach be dropped for the present as means of providing pulse shortening or synchronization of short pulses.

33.We used the nonlinear polarization rotation in a 20 meter long section of single mode single core fiber to reduce the pulse duration to about 2 psec. We accomplished the nonlinear polarization rotation shaping by using polarizers and wave retarders before and after a 20 m section of single core fiber.

7.5 July-November 95

July 95

34. We investigated Mach-Zehnder modulators to determine the best modulator as regards stability against intensity induced degradation. Mr. Kaechele told us that there was a gradual reduction in power from the Rome version of the HML laser during operation. One cause of power reduction during operation can be light induced distortion of the lithium niobate in the modulator. This does not seem likely since the Rome laser modulator uses proton exchanged guides that should be more resistant to temporary optical damage.(We did not resolve this issue during the period of performance.)

35. We made plans to synchronize the HML laser at Rome with a standing wave fiber laser at Rome. Dr. Teegarden has been developing a standing wave saturable absorber modelocked laser at Rome Laboratory. Dr. Teegarden located this laser in the same laboratory as the HML laser. The standing wave laser uses a fiber Bragg grating reflector at one end of the fiber and a multiple quantum well saturable absorber at the other.

The above provides a chronological account of the work performed. We schematically diagram the laser in Fig.1. We give some representative data characterizing the laser in Fig. 2 and Fig. 3. We did not acquire all of this information during the period of performance, but we have made the list relatively complete for convenience of those who may wish to refer to this material.

8. Conclusions

We conclude that the original concept recommending synchronized harmonically modelocked (HML) lasers for investigation was accurate. We demonstrated a capacity to produce stable trains of high repetition rate pulses with good mode quality. We also demonstrated synchronization of two lasers. We expect additional work will move this technology to a state where it is sufficiently robust and compact for application in Air Force systems.

The recent discovery of double clad amplifier techniques has further emphasized the value of this technology. Access to very high degrees of parallelism, high average powers, excellent mode quality, short pulse duration, and stable pulse envelopes all appear to be accessible.

Directions for future development will probably include means for producing synchronized signals at a variety of wavelengths, gating and modulating those signals, developing phase control of the various signals, providing means for generating and receiving signals, and developing the complex

agile circuitry for controlling and processing this variety of signals. We anticipate that extensive diagnostics and many active feedback loops will be important in these systems.

We incidentally performed additional work, not under this contract, on photonic band gap delay lines. These devices appear to offer a novel and potentially powerful means of adjusting temporal delays for 1.55 micron light in very compact structures. We recommend that future work on these systems consider these delay lines as a technology that could be important. We believe incorporation on, e.g., a microchip may be possible.

9. Figure Captions

Figure 1: Diagram of the harmonically modelocked laser and relation to synchronized laser.

Figure 2. Spectrum of modelocked laser obtained from scanning interferometer.

Figure 3. Autocorrelation trace of pulse from modelocked laser including polarization shaping.

10.Acknowledgments

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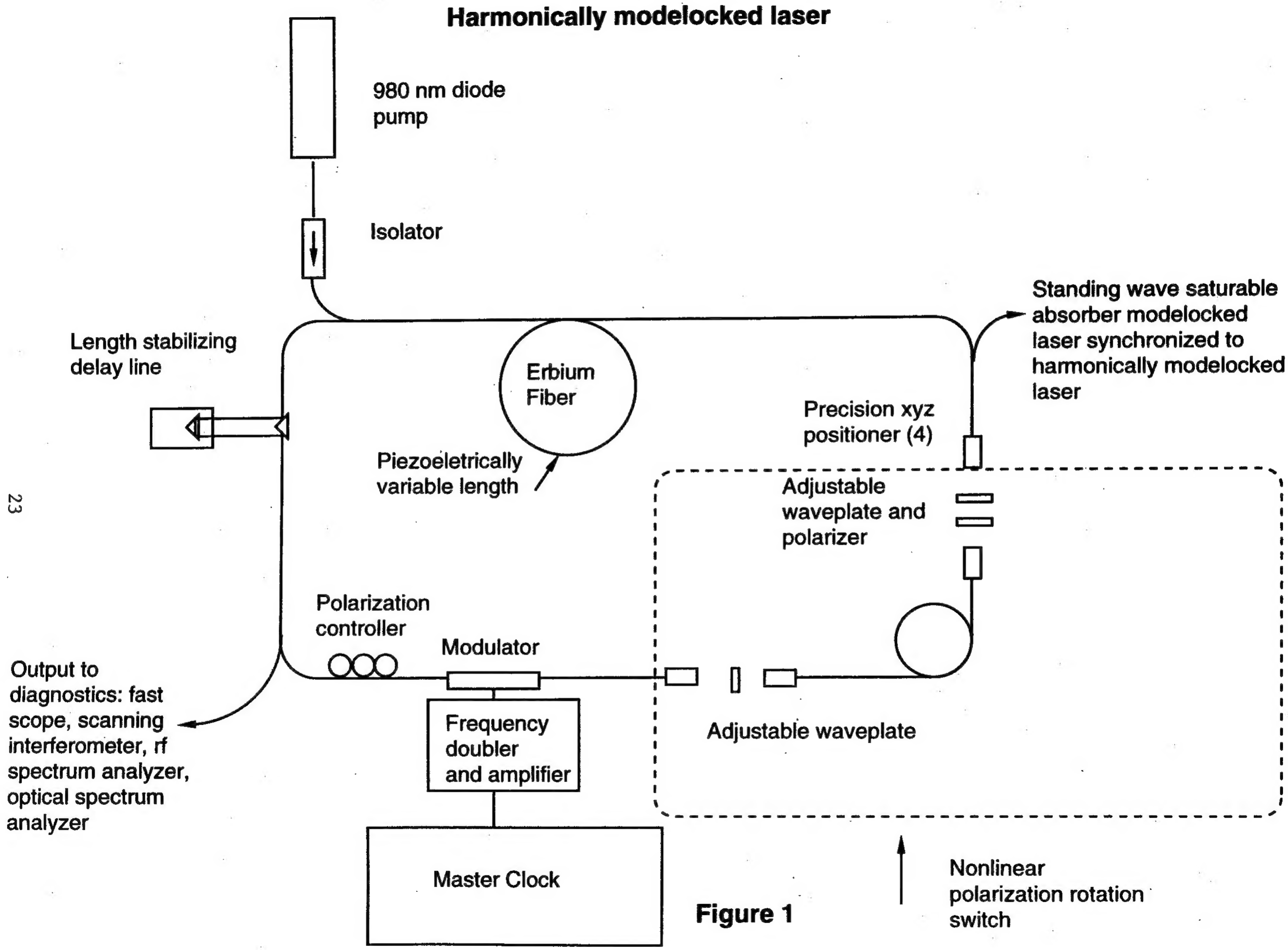
Harmonically modelocked laser
980 nm diode pump
Isolator
Length stabilizing delay line
Erbium Fiber
Piezoeletrically variable length
Standing wave saturable absorber modelocked laser synchronized to harmonically modelocked laser
Precision xyz positioner (4)
Adjustable waveplate and polarizer
Polarization controller
Modulator
Output to diagnostics: fast scope, scanning interferometer, rf spectrum analyzer, optical spectrum analyzer
Frequency doubler and amplifier
Adjustable waveplate
Master Clock
Nonlinear polarization rotation switch

Figure 1

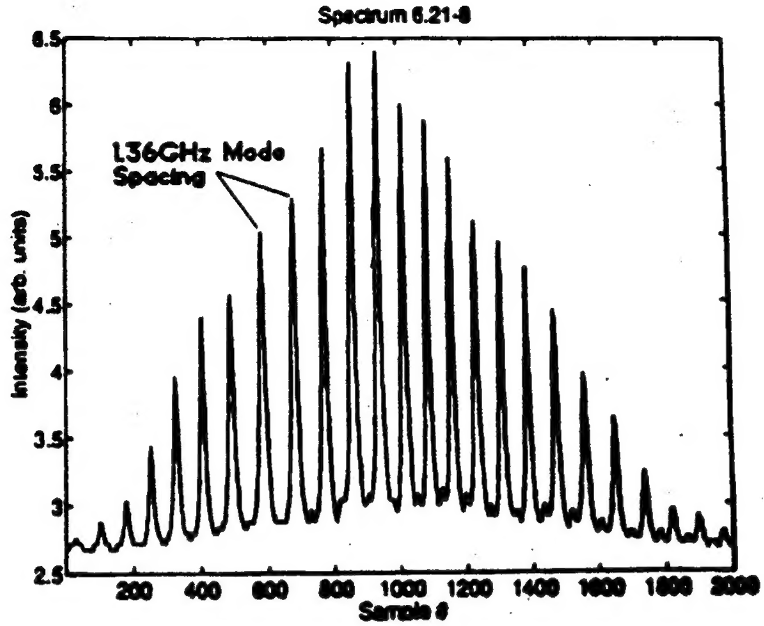

Fig. 2

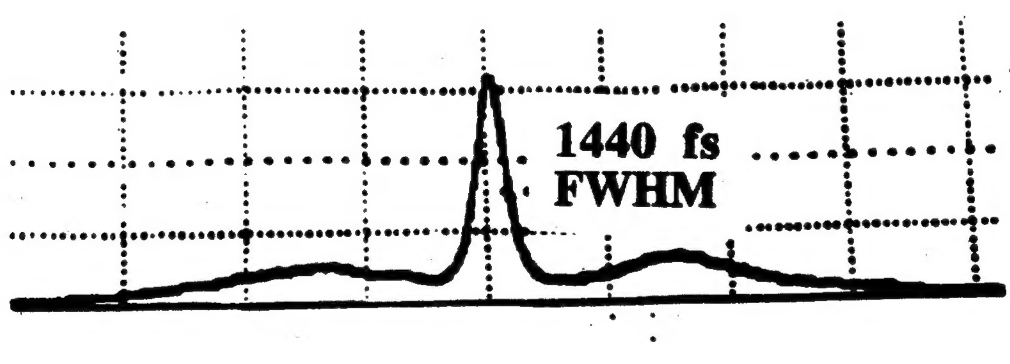

Fig. 3

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